

Experimental investigation of laboratory-scale granular landslide impacting on dry and liquid surfaces

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Abstract. Granular materials display a wide range of behaviours in natural phenomena such as avalanches and landslides. The focus of the present work is to experimentally study and compare the run-off dynamics of the laboratory-scale granular landslide impacting on a horizontal dry surface of varying roughness. Various grades of industrial sandpaper (80, 600, and 1000 grit) are used to study how the surface properties modify the frictional interaction between the particles and the surface. Wet granular experiments are performed to study the effect of a water body (water depths of 5 mm and 10 mm) in front of the landslide to control the flow. Through systematic experimentation, a broad range of parameters, including flow speeds, slope angles, and the surface friction of a depository table, are investigated to delineate interaction characteristics. Granular flow is studied for different angles of inclination (35°-60°) and compared using spread area, run-off distance, and height of the terminated flow. At lower angles, the run-off distance experiences a reduction of approximately 50% for the frictional surface. Additionally, the potential use of water bodies as a control measure shows promising results. The observations suggest a potential defence mechanism for controlling hazardous landslide scenarios. These findings provide valuable insights into the dynamics of granular flows and would stimulate future research in this area.

1 Introduction

Granular materials can behave as solid particles shaping natural phenomena like erosion and avalanches. The study of granular materials is vital in fields like physics, geology, and engineering, aiding in structural design and the prediction of natural disasters. Landslides involve many particles of different masses cascading downwards, they collide with each other and spread out across the surface until they eventually come to rest. Large-scale granular movements like landslides, avalanches, and debris flows [1,2] pose serious threats to human life and infrastructure [3]. Studying the dynamics of granular flows is critical for understanding and combating natural hazards [4]. Gravity-induced granular flows exhibit similarities to those observed in landslides [5]. The swift descent of soil, rock, and debris during landslides illustrates the collective movement of granular particles driven by gravity, marked by inelastic collisions and energy dissipation [6,7]. Extensive research has been conducted to unravel the complex mechanisms of landslides, aiming to better understand their dynamics and associated risks [8-10]. The integration of advanced technologies—such as remote sensing, numerical modeling, and real-time monitoring—has significantly advanced the development of early warning systems. Despite extensive efforts to study landslide dynamics, there has been less focus on developing strategies to

mitigate their consequences [11,12]. Controlling the flow of granular material through barrier establishment is crucial for reducing the impact of hazardous events. Studies indicate that an erodible bed extends run-out distances and highlight the need to consider bed conditions in predictions [13]. The present work aims to explore the role of impacting surfaces in controlling granular flows. The study focuses on the dynamics of granular flow to propose mitigation strategies against landslides. It studies the laboratory-scale gravity-driven granular landslide impacting on a horizontal dry surface of varying roughness and water pool of varying depth. The spread dynamics of the debris on these surfaces are compared. The study offers insights into how granular flow characteristics are modulated and how damping effects occur in both dry and wet conditions. It helps in understanding the interactions between granular materials and impacting surfaces.

2 Methodology

2.1 Experimental Setup

Figure 1 shows the schematic of the experimental setup consisting of a hopper, a chute, and a ground table. The hopper features a controllable lid mechanism for regulating flow (flow gate). The opening gate size of 290 x 7 mm is designed to prevent jamming [6]. The ground table provides the platform for visualizing flow patterns.

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Different friction conditions are achieved using industry-grade sandpaper sheets. The grains used are transparent glass beads of diameter 0.8~1 mm and a density of 2500 kg/m³. The density is corresponding to that of the rock debris [14]. The chute angle (θ) is varied from 35°-60°, thereby altering the mass flow rate.

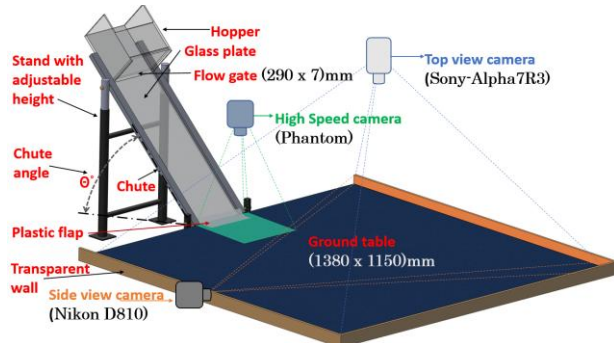


Fig. 1. Schematic diagram of the experimental setup.

The experimental setup uses three cameras to allow simultaneous visualization from multiple perspectives for detailed analysis of the granular flow. Following data acquisition, image processing is utilized for post-processing of the images, enabling measurement of the spread area, run-off length, deposition shape, and height of the deposited flow. For the top view a Sony Alpha 7R3 camera is used to capture the final pattern and a Phantom VEO 710L high-speed camera is used to see the deposit pattern at different time stamps. The side view is captured using Nikon D810. Four cases of dry surface are studied in the work, sunmica and 3 sandpaper surfaces (80, 600, and 1000 grit), with 80 grit having the highest friction. Two water depths of (5 mm and 10 mm) are used to analyse water level impact on the damping properties. Particles are dispensed through a hopper via a flow gate and are terminated at the ground table, simulating real-life conditions. For each experiment, 1.5 kg of material is used. Multiple realizations are conducted to ensure repeatability and minimize uncertainty.

2.2 Parameters to Analyse

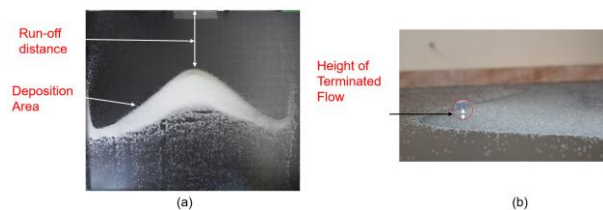


Fig. 2. (a) Top view and (b) Side view of terminated flow on the ground table.

Figure 2 illustrates the deposit pattern of the terminated flow on a smooth surface and shows the parameters used for analysis. The spread area (total area of granular material spread on the ground table under different conditions), the run-off distance (distance from the table inlet to the first point of terminated granular flow), and the maximum height of the terminated flow are measured. For a particular chute angle (θ), non-dimensional spread area (A^*), maximum deposit height (D^*), and run-off distance (L^*) are defined as follows:

$$A^* = \frac{A}{(\bar{u} * t)^2} \quad (1)$$

$$D^* = \frac{D}{(\bar{u} * t)} \quad (2)$$

$$L^* = \frac{L}{(\bar{u} * t)} \quad (3)$$

Where A is the spread area of the deposit, \bar{u} is the mean impact velocity, t is the time required for flow termination, D is the maximum height of the deposit and L is the run-off distance. Particle image velocimetry analyses are performed to measure the mean impact velocity of the particle corresponding to the chute angle.

3 Results and Discussions

3.1 Flow Structure

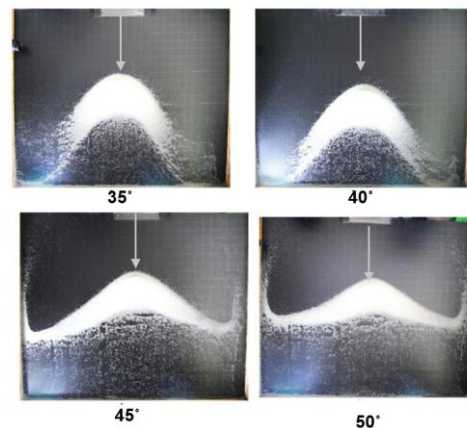


Fig. 3. Flow structure variation with chute angle for the smooth surface.

Figure 3 shows the results of the terminated flow for the smooth surface. As the inlet velocity increases with the inclination angle, the flow structure changes, forming a mustache-like structure. The flow dynamics reveal a complex interaction of lateral and longitudinal movements, resulting in the formation of distinct flow structures. Friction surfaces are used to understand the impact of terrain roughness on run-off dynamics.

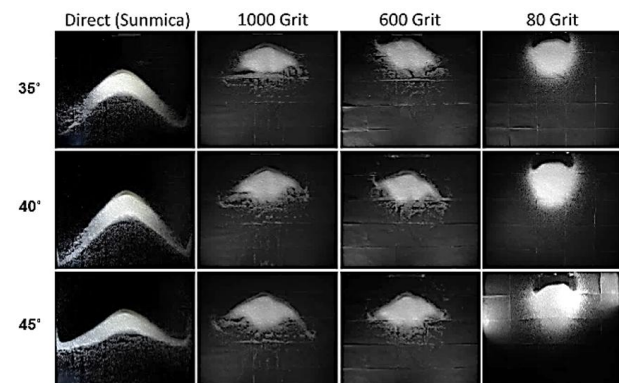


Fig. 4. Terminated flow structure comparison for all dry surfaces at different angles (θ).

Figure 4 provides an overview of the deposited flow pattern under different inclination angles (θ) and friction conditions. The frictional conditions progressing from sunmica to the highest friction from left to right. There is

a decrease in the spread area and moustache shaped structure is changed to a conventional tongue-like structure with the introduction of the friction surface. With an increase in chute angle the included angle of the mustache-like structure also increases, indicating that higher speeds result in more lateral scatter. This counterintuitive observation shows that with an increased particle momentum, the spread is more in the sideways direction rather than along the flow. The angle of deposit on the ground table is highest for the least friction case and decreases as friction increases. Additionally, a wider spread area is observed under both low and high friction conditions, while a narrow spread occurs on medium friction surfaces.

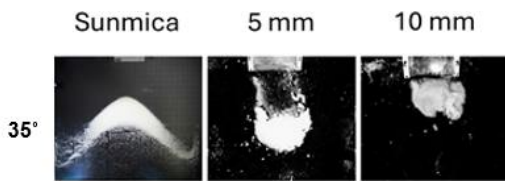


Fig. 5. Terminated flow structure for water pool & smooth case at $\theta=35^\circ$.

Figure 5 shows the deposited structure at 35° for two water pool heights, compared to a dry smooth surface. The presence of water significantly reduces the run-off distance and area of the deposited pattern due to the high resistance it poses to the granular material, hindering its movement. In water, the flow expands into two counter-rotating flows with a central mean flow, creating a tongue-shaped structure. For the dry flow case, the deposited structure tip is towards the chute while for the wet surface, the tip is in the opposite direction.

3.2 Parameters Evaluations

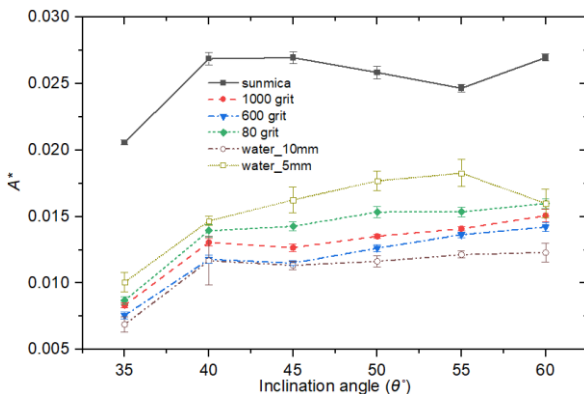


Fig. 6. Non-dimensional spread area for all surfaces at different inclination angles (θ).

The results for the non-dimensional spread area are shown in Figure 6. For dry granular flow, the spread area of deposited material is highest for sunmica due to its smoothness. The spread area fluctuates with different friction conditions. Notably, both high and low friction conditions result in a slightly higher spread area compared to medium friction. Therefore, it can be concluded that both high and very low friction adversely increase the spread area. At lower friction (1000 grit), the low friction coefficient reduces energy dissipation, resulting in lower velocity reduction and higher material spread. At higher

friction (80 grit), significant energy dissipation during particle-surface collisions reduces velocity, causing new layers to form behind the previous layer. This results in a lower run-off distance. At medium friction (600 grit), a balance between energy dissipation and particle velocity is achieved, forming layers both atop the previous layer and independently, exhibiting characteristics of both high and low friction conditions. The results suggest that the medium friction surfaces have potential utility as a defence mechanism for controlling the spread of landslide scenarios. Wet flow results suggest that greater water height offers more resistance to the granular flow thereby reducing particle spread. Additionally, an increase in the inclination angle (θ) results in a slight increase in deposit area, as higher particle momentum leads to greater scatter with increased angle.

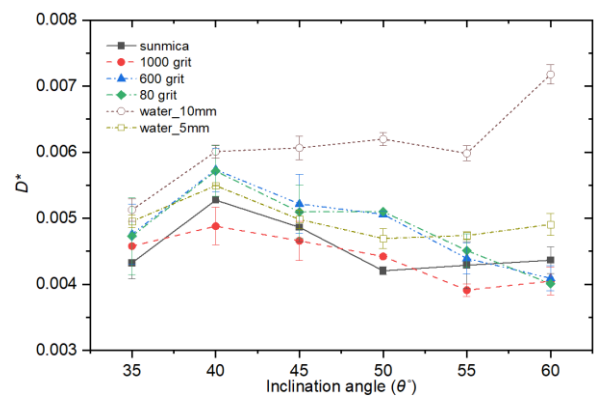


Fig. 7. Non-dimensional maximum deposit height for all surfaces studied in this work.

Figure 7 represents the non-dimensional maximum deposit height for all surface conditions studied in the work. The results show that for dry granular flow, the maximum deposit height increases with friction. Interestingly, on medium-friction surfaces (600 grit), the deposit height is even greater, consistent with previous findings of a reduced spread area. Additionally, as the angle of inclination (θ) increases, the maximum height decreases for dry cases. This is because higher velocities at increased angles cause the deposit to travel further, reducing overall height. At lower angles, the material tends to accumulate in layers, resulting in a higher deposit height. For wet granular flow, the span-wise spread of the deposit is uneven. The deposition height is dependent on the water pool height.

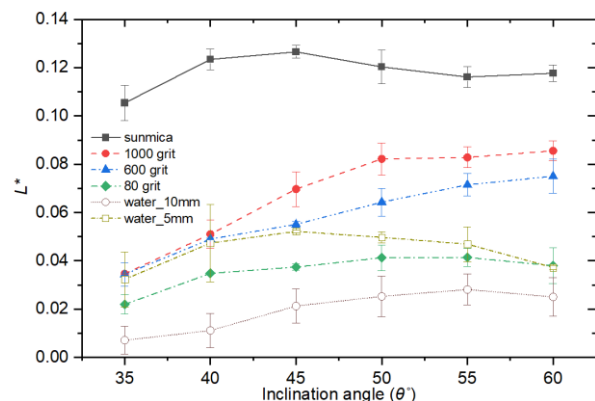


Fig. 8. Non-dimensional run-off distance for all surfaces at different inclination angles (θ).

Figure 8 presents the non-dimensional run-off distance at different inclination angles (θ). For frictional surfaces at lower angles, the run-off distance experiences a reduction of approximately 50% from its value for the smooth surface. As the inclination angle (θ) increases there is a proportional rise in run-off distance. Beyond a critical angle (50° - 60°), the run-off distance stabilizes. At lower angles, higher velocity increments cause the flow to travel further, significantly increasing the run-off distance. Conversely, at higher angles, smaller velocity changes stabilize the run-off distance. For dry granular flow, the increment in run-off distance with increased inclination is higher, while for wet granular flow, the increment is lower due to higher resistance. As friction increases with either surface roughness or water height, the run-off distance decreases for both dry and wet granular flow. This decrement is more pronounced for dry granular flow and minimal for wet granular flow, with values for wet granular flow being significantly lower.

4 Conclusions

The study reveals the formation of distinct deposit patterns on the run-off area, ranging from a new Mustache-like structure under low friction conditions to a more well-known tongue-shaped structure under high friction conditions. For medium friction, there exists a balance between energy dissipation and particle velocity. This results in the formation of layers both atop the previous layer and independently, exhibiting characteristics of both high and low friction conditions. Consequently, the spread area is lower compared to other conditions. For lab-scale landslides impacting on water, it is observed that as the height of water increases, the value for maximum deposit depth also increases. For dry cases at lower angles, the depth of the deposit tends to be greater. This phenomenon arises due to the material's propensity to accumulate in layers atop one another, resulting in a higher overall deposit depth. Conversely, at higher angles where the spread of material is more pronounced, the deposit depth tends to decrease. In summary, the study indicates that the behaviour of granular flows, both dry and wet, is significantly influenced by the inclination angle and surface friction conditions. Dry cases are more sensitive to changes in friction, showing higher spread and run-off distances at lower friction levels. The findings indicate that medium-friction surfaces and water pools could serve as effective defensive strategies for controlling hazardous landslide scenarios.

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